

MCGINN & GIBB, P.C.
A PROFESSIONAL LIMITED LIABILITY COMPANY
PATENTS, TRADEMARKS, COPYRIGHTS, AND INTELLECTUAL PROPERTY LAW
1701 CLARENDON BOULEVARD, SUITE 100
ARLINGTON, VIRGINIA 22209
TELEPHONE (703) 294-6699
FACSIMILE (703) 294-6696

**APPLICATION
FOR
UNITED STATES
LETTERS PATENT**

APPLICANT: **Hiroyuki Saito**

FOR: **APPARATUS AND METHOD FOR
DESIGNING COMMUNICATION
PATHS OF TREE STRUCTURE**

DOCKET NO.: **NE-1017-US/KM**

004T40" 2795T960

TITLE OF THE INVENTION**Apparatus and Method for Designing Communication Paths of Tree
Structure**BACKGROUND OF THE INVENTIONField of the Invention

The present invention relates generally to communication networks and more particularly to the design of communication paths of tree structure within a communication network between an ingress node and an egress node the network.

Description of the Related Art

In a label-switched communication system, such as ATM (asynchronous transfer mode) and MPLS (multiprotocol label switching) systems, an active communication path is provisioned between an ingress node and an egress node for carrying normal traffic and, in most cases, one or more spare paths are provisioned for purposes of protection switching or distributing overflow traffic. However, a large number of virtual channel identifiers (VCIs) and virtual path identifiers (VPIs) must be registered if all possible routes are provisioned between all pairs of ingress and egress nodes. In order to overcome this problem, a technique known "VP/VC merge" has been proposed, whereby multiple communication paths are provisioned using a single VPI or VCI.

In a communication system where a single VPI/VCI is used for identifying multiple paths provisioned between an ingress and an egress node, the structure of the paths is treated as a tree and the egress node assumes the root of the tree so that traffic is carried in the opposite sense. It is

09616672.071400

1 thus desirable that the number of such trees be as small as possible to reduce
2 the number of labels (i.e., VPIs and VCIs) to a minimum.

3 One approach to designing a tree is to use the Dijkstra method
4 ("Saitekika Handbook, Iri et al, Asakura Shoten publishing company),
5 whereby all possible routes from one egress node to each ingress node are
6 searched for in an attempt to determine shortest paths from which a tree is
7 formed. A tree is formed by a technique known as the minimum spanning
8 tree method ("Enshuu Graph Riron", Iri et al, Korona-sha publishing
9 company), in which the tree is defined as one in which the total sum of
10 branch metrics is at a minimum. Such a tree can be obtained by a technique
11 known as the Kruskal method.

12 While the known techniques allow provisioning of a single tree
13 between an ingress node and an egress node, it is impossible to design a
14 plurality of trees between these nodes.

15 SUMMARY OF THE INVENTION

16 It is therefore an object of the present invention to provide an apparatus
17 and method for designing a plurality of trees within a communication network.
18 The communication path of each tree is independent from every other paths of
19 the tree. Thus, in each tree, nodes and links are not shared by different
20 communication paths.

21 Another object of the present invention is to provide an apparatus and
22 method for designing a plurality of communication paths within a
23 communication network with a minimum number of trees.

24 According to a first aspect of the present invention, an objective function
25 is defined for minimizing a number of candidate tree graphs for

09616672-071400

1 accommodating said communication paths and a first constraint equation is
2 defined for causing all of the candidate tree graphs to form a tree. A second
3 constraint equation is defined for accommodating the communication paths in
4 one of the candidate tree graphs. A third constraint equation is defined for
5 determining whether each of the candidate tree graphs is used to accommodate
6 the communication paths. A mathematical programming problem formed by
7 the objective function, and the first, second and third constrain equations is
8 solved to obtain a plurality of trees in which the communication paths can be
9 accommodated.

10 According to a second aspect of the present invention, an existing tree is
11 stored and a decision is made as to whether communication paths can be
12 accommodated in the existing tree. An objective function is defined for
13 minimizing a number of candidate tree graphs for accommodating those
14 communication paths which cannot be accommodated in the existing tree. A
15 first constraint equation is defined for causing all of the candidate tree graphs
16 to form a tree if all of the communication paths cannot be accommodated in
17 the existing tree. A second constraint equation is defined for accommodating
18 those communication paths that cannot be accommodated in the existing tree
19 in one of the candidate tree graphs. A third constraint equation is defined for
20 determining whether each of the candidate tree graphs is used to accommodate
21 at least one of the communication paths. A mathematical programming
22 problem formed by the objective function, and the first, second and third
23 constrain equations is solved to obtain a plurality of trees in which those
24 communication paths that cannot be accommodated in the existing tree can be
25 accommodated.

09616672-071400

1 According to a third aspect of the present invention, a first constraint
2 equation is defined for causing all candidate tree graphs to form a tree and a
3 second constraint equation is defined for accommodating communication
4 paths in one of the candidate tree graphs. Non-negative artificial variables are
5 embedded into the first and second constraint equations. An objective function
6 is defined for minimizing a total number of the non-negative artificial
7 variables. A mathematical programming problem formed by the objective
8 function and the first and second constrain equations is solved to obtain a
9 plurality of trees in which the communication paths can be accommodated.

10 According to a fourth aspect of the present invention, an existing tree is
11 stored and a decision is made as to whether communication paths can be
12 accommodated in the existing tree. A first constraint equation is defined for
13 accommodating those communication paths which cannot be accommodated
14 in the existing tree in one of candidate tree graphs. A second constraint
15 equation is defined for causing all of the candidate tree graphs to form a tree.
16 Non-negative artificial variables are embedded into the first and second
17 constraint equations. An objective function for minimizing a total number of
18 the non-negative artificial variables. A mathematical programming problem
19 formed by the objective function, and the first and second constrain equations
20 is solved to obtain a plurality of trees in which those communication paths
21 which cannot be accommodated in the existing tree can be accommodated.

22 BRIEF DESCRIPTION OF THE DRAWINGS

23 The present invention will be described in further detail with reference
24 to the accompanying drawings, in which:

25 Fig. 1 is a block diagram of a communication network in which a

09616672.071400

1 plurality of communication paths are established in the form of a tree as
2 viewed from an egress node;

3 Fig. 2 is a block diagram of an apparatus for designing communication
4 paths within a communication network according to a first embodiment of
5 the present invention;

6 Fig. 3 is a flowchart for operating the design apparatus of Fig. 2;

7 Fig. 4 is a modified flowchart of Fig. 3;

8 Fig. 5 is a block diagram of a design apparatus of the present invention
9 according to a second embodiment;

10 Fig. 6 is a flowchart for operating the design apparatus of Fig. 5;

11 Fig. 7 is a block diagram of a design apparatus according to a third
12 embodiment of the present invention;

13 Fig. 8 is a flowchart for operating the design apparatus of Fig. 7;

14 Fig. 9 is a block diagram of a design apparatus according to a fourth
15 embodiment of the present invention; and

16 Fig. 10 is a flowchart for operating the design apparatus of Fig. 9.

17 DETAILED DESCRIPTION

18 Fig. 1 represents a fault tolerant communication network in a directed
19 graph for purposes of explanation of the present invention. As illustrated, the
20 network comprises a plurality of edge nodes $e_1 \sim e_{10}$ and a plurality of core
21 (intermediate) nodes $c_1 \sim c_5$. Each edge node is called an ingress node if it
22 receives incoming traffic from end user systems or an egress node if it
23 delivers outgoing traffic to end user systems. Edge nodes $e_1 \sim e_{10}$ are
24 connected to adjacent core nodes as indicated by thin lines 10. Each of the
25 core nodes $c_1 \sim c_5$ is connected to every other core nodes as indicated by a thin

09616672.071400

1 line 11.

2 As opposed to the usual tree graph representation in which the root
3 node is connected by directed arcs (links) to the remaining nodes, the egress
4 node is taken as a root node in the present invention and the links are
5 directed towards the root (egress) node, rather than towards the remaining
6 nodes. A link from one node to any of the other nodes is denoted by an
7 ordered pair of nodes such as (e_7, c_4) .

8 A communication path from an ingress node to an egress node is
9 represented by an ordered set of nodes such as $e_7-c_5-c_1-e_1$. A set of such
10 communication paths from a number of ingress nodes to the egress node
11 forms a "tree" as viewed from the egress (root) node. For example, if it is
12 desired to establish in the communication network a first path $e_7-c_5-c_2-e_1$, a
13 second path $e_7-c_4-c_3-e_1$, a third path $e_3-c_2-e_1$ and a fourth path $e_3-c_3-c_4-c_1-e_1$,
14 the first, second, third and fourth paths can be accommodated by thick lines
15 12, 13, 14 and 15, respectively.

16 According to the present invention, an apparatus for designing paths
17 of a tree structure within a communication network is shown in Fig. 2. The
18 design apparatus includes a computer 100, an input device 106 such as a
19 keyboard, an output device 107 such as a display unit, and a storage medium
20 108 which may be a floppy disk or a read-only memory. Computer 10
21 includes an optimization reference generation unit 101, a tree forming
22 condition generation unit 102, a path accommodation condition generation
23 unit 103, a tree utilization decision threshold generation unit 104 and an
24 optimization unit 105. A program is stored in the storage medium 108 for
25 instructing the computer 110 to control its internal units to perform their

09616672-071400

1 functions according to the flowchart of Fig. 3.

2 First, the input device 106 is used to enter network topology data
3 representing a communication network. Such topology data includes a
4 plurality of candidate tree graphs. Each of the candidate tree graphs consists
5 of identifiers specifying edge nodes, core nodes and links interconnecting
6 these nodes, identifiers specifying an ingress node and an egress node and a
7 "set" of available paths between the ingress node and the egress node.
8 Additionally, the topology data includes the number of the candidate tree
9 graphs.

10 In response to the input data, the optimization reference generation
11 unit 101 produces an objective function at step 301 (Fig. 3) according to
12 Equation (1) as follows:

$$\text{Minimize } \sum_{t_e \in T_e} r^{t_e} \quad (1)$$

13 where, t_e represents a candidate tree graph at an egress node "e", T_e
14 represents a set of such candidate tree graphs at the egress node "e" and r^{t_e} is
15 a variable which assumes 1 when the candidate tree graph t_e is used to
16 accommodate a path from an ingress node, or 0 otherwise. The objective
17 function of Equation (1) minimizes the number of candidate tree graphs used
18 to accommodate given communication paths.

19 At step 302, the tree forming condition generation unit 102 defines the
20 following Equations (2), (3) and (4) that constrain candidate tree graphs so
21 that the elements (nodes) of the graphs are connected to form a tree.
22 Equations (2), (3) and (4) are defined by setting the egress node of a network
23 flow problem as a source and the of ingress and core nodes as a sink.

$$\sum_{\{m:(\ell,m) \in L^{e-c}\}} f_{(\ell,m)}^{t_e} = 1 \quad (\forall t_e \in T_e, \forall \ell \in N^{edge} \setminus \{e\}) \quad (2)$$

$$\begin{aligned} & \sum_{\{m:(\ell,m) \in L^{c-c}\}} f_{(\ell,m)}^{t_e} - \sum_{\{m:(\ell,m) \in L^{c-c}\}} f_{(m,\ell)}^{t_e} \\ & + o_{(\ell,e)} f_{(\ell,e)}^{t_e} - \sum_{\{m:(m,\ell) \in L^{e-c}\}} f_{(m,\ell)}^{t_e} = 1 \\ & (\forall t_e \in T_e, \forall \ell \in N^{edge} \setminus \{e\}) \end{aligned} \quad (3)$$

$$\begin{aligned} \sum_{\{m:(\ell,e) \in L^{e-c}\}} f_{(\ell,e)}^{t_e} &= |N^{edge}| + |N^{core}| - 1 \\ & (\forall t_e \in T_e) \end{aligned} \quad (4)$$

1 where, $f_{(l,m)}^{te}$ represents the amount of traffic carried by a link (l, m) of a
 2 candidate tree graph t_e , where “l” and “m” are source (upstream) and
 3 destination (downstream) nodes of the link, N^{edge} is a set of edge nodes, and
 4 L^{e-c} is a set of links that interconnect core nodes and edge nodes. L^{c-c}
 5 represents a set of links interconnecting core nodes, $o_{(l,e)}$ is a variable which
 6 assumes 1 when a link (l, e) exists between a core node “l” and the egress
 7 node “e”, or 0 otherwise, and N^{core} represents a set of core nodes.

8 Equation (2) indicates that the ingress node is a source and Equation
 9 (3) indicates that the core nodes are sources, while Equation (4) indicates that
 10 the egress node is a sink where it absorbs the traffic $|N^{edge}| + |N^{core}| - 1$.

11 In order to constrain the links so that its number equals the number of
 12 nodes minus one, constraint Equation (5) is determined as follows:

$$\begin{aligned} & \sum_{(l,m) \in L^{c-c}} h_{(l,m)}^{t_e} + \sum_{\{(l,e) \in L^{e-c}\}} h_{(l,e)}^{t_e} + \sum_{l \in N^{edge} \setminus \{e\}} \sum_{\{m:(l,m) \in L^{e-c}\}} h_{(l,m)}^{t_e} \\ & = |N^{core}| + |N^{edge}| - 1 \quad (\forall t_e \in T_e) \end{aligned} \quad (5)$$

13 where $h_{(l,m)}^{te}$ is a variable that assumes 1 when the candidate tree graph t_e

1 uses a link (l, m) , or 0 otherwise. Since the variable used in Equations (2) to
 2 (4) is different from the variable used by Equation (5), it is necessary to
 3 establish relationships between these different variables. For this reason, the
 4 following constraint Equations (6) to (8) are defined:

$$Mh_{(l,e)}^{te} \geq f_{(l,e)}^{te} \quad (\forall t_e \in T_e, \forall (l,e) \in L^{e-c}) \quad (6)$$

$$Mh_{(l,m)}^{te} \geq f_{(l,m)}^{te} \quad (\forall t_e \in T_e, \forall (l,m) \in L^{c-c}) \quad (7)$$

$$Mh_{(l,m)}^{te} \geq f_{(l,m)}^{te} \quad (\forall t_e \in T_e, \forall (l,m) \in L^{e-c}, \forall l \in N^{edge} \setminus \{e\}) \quad (8)$$

5 where, M is an integer of sufficiently large value. Equation (6) defines the
 6 relationships between the variables of the links interconnecting the core
 7 nodes and Equation (7) defines the relationships between the variables of the
 8 links directed from core nodes to the egress node. Equation (8) defines the
 9 relationships between the variables of the links directed from ingress nodes to
 10 core nodes.

11 Note that the fourth terms $f_{(l,m)}^{te}$ and $f_{(m,l)}^{te}$ of Equations (2) and (3)
 12 may be replaced with $h_{(l,m)}^{te}$ and $h_{(m,l)}^{te}$, respectively. In this case, Equation
 13 (8) is not necessary. Alternatively, Equation (5) can be modified as Equation
 14 (9) given below:

$$\sum_{(l,m) \in L^{c-c}} h_{(l,m)}^{te} + \sum_{\{l:(l,e) \in L^{e-c}\}} h_{(l,e)}^{te} = |N^{core}| \quad (\forall t_e \in T_e) \quad (9)$$

15 At step 303, the path accommodation condition generation unit 103
 16 produces Equations (10) and (11) as follows in order to accommodate the
 17 given paths into the candidate tree graph:

09515572.071400

$$\sum_{(l,m) \in \{L^{P(i,e)} \cap L^{e-c}\}} h_{(l,m)}^{t_e} + \sum_{(l,m) \in \{L^{P(i,e)} \cap L^{e-c}\}} h_{(l,m)}^{t_e} \geq |L^{P(i,e)}| \delta_{P(i,e)}^{t_e} \quad (p(i,e) \in P_{(i,e)}, i \in N^{edge} \setminus \{e\}, t_e \in T_e) \quad (10)$$

$$\sum_{t_e \in T_e} \delta_{P(i,e)}^{t_e} \geq 1 \quad (\forall p(i,e) \in P_{(i,e)}, \forall i \in N\{e\}) \quad (11)$$

1 where, $p_{(i,e)}$ is the element of a set of links $P_{(i,e)}$ between an ingress node "i"
 2 and an egress node "e" and $\delta_{p(i,e)}^{t_e}$ is a variable that assumes 1 when the
 3 candidate tree graph t_e includes the path $p_{(i,e)}$, or 0 otherwise. In Equation
 4 (10) the variables $h_{(l,m)}^{t_e}$ associated with links used by paths $p_{(i,e)}$ are
 5 summed. If the sum is equal to the number of hops of the path $p_{(i,e)}$, Equation
 6 (10) indicates that the path $p_{(i,e)}$ is accommodated in the candidate tree graph
 7 t_e .

8 At step 304, the tree utilization decision threshold generation unit 104
 9 produces Equation (12) that determines whether a candidate tree graph is
 10 used for accommodating the path.

$$\sum_{i \in N^{edge} \setminus \{e\}} \sum_{p(i,e) \in P_{(i,e)}} \delta_{p(i,e)}^{t_e} \leq Mr^{t_e} \quad (\forall t_e \in T_e) \quad (12)$$

11 According to Equation (12), the variable r^{t_e} is set equal to 1 even if there is
 12 only one candidate tree graph t_e that accommodates a path.

13 Finally, at step 305, the optimization unit 105 uses a simplex method to
 14 solve the mathematical programming problem formed by objective function
 15 (1) and constraint Equations (2) to (12) defined by the units 101, 102, 103 and
 16 104 to obtain a minimum number of trees. If it is desired to design a path
 17 from the ingress node to more than one egress node, the process of Fig. 3 may
 18 be repeated for each of the egress nodes.

19 The design algorithm of Fig. 3 may be modified as shown in Fig. 4

1 which differs from the previous embodiment in that the tree forming
2 condition generation unit 102 performs step 402 instead of step 302 of Fig. 3.

3 At step 402, the tree forming condition generation unit 102 produces
4 Equations (2) to (4) as described above and then Equations (13) and (14) for
5 using only one of the links that emanate from source nodes which include the
6 ingress node and all core nodes.

$$\sum_{\{m:(l,m) \in L^{c-c}\}} h_{(l,m)}^{t_e} + o_{(l,e)} h_{(l,e)}^{t_e} = 1 \quad \left(\forall l \in N^{\text{core}}, \forall t_e \in T_e \right) \quad (14)$$

$$\sum_{\{m:(l,m) \in L^{c-c}\}} h_{(l,m)}^{t_e} = 1 \quad \left(\forall l \in N^{\text{edge}} \setminus \{e\}, \forall t_e \in T_e \right) \quad (13)$$

7 Equation (13) is used for constraining the links that emanate from the
8 ingress node to one link, and Equation (14) is used for constraining the links
9 that emanate from all core nodes to one link. Equation (3) may be altered as
10 Equation (15) as follows if the core nodes are not treated as sources.

11 Apparatus of Fig. 2 may be modified as shown in Fig. 5 by additionally
12 including an existing tree memory 501 for storing a set of existing trees
13 entered through the input device 106.

14 The flowchart of Fig. 3 may be further modified as shown in Fig. 6 to
15 control the computer 100 of Fig. 5. In this modification, the existing trees
16 from the input device 106 are stored in the memory 501 at step 601. At step
17 602, the CPU of computer 100 reads a stored existing tree t_e from the memory
18 and determines whether a desired path $p_{(i,e)}$ can be accommodated in the
19 read existing tree t_e (step 603) by using the following decision Equation (16)
20 given below.

004472074400

$$\sum_{(\ell, m) \in \left\{ L^{P(i, e)} \cap L^{c-c} \right\}} j_{(\ell, m)}^{t_e} + \left\{ \sum_{(\ell, m) \in \left\{ L^{P(i, e)} \cap L^{e-c} \right\}} j_{(\ell, m)}^{t_e} \right\} = \left| L^{P(i, e)} \right| \quad (16)$$

1 where, $j_{(\ell, m)}^{t_e}$ is a variable which assumes 1 if the existing tree t_e is using the
 2 link (l, m) or 0 otherwise. If all the given communication paths can be
 3 accommodated in the read existing tree, the decision is affirmative at step 603
 4 and flow proceeds to step 604 to check to see if all existing trees are tested. If
 5 so, the computer proceeds to the end of the routine. Otherwise, flow returns
 6 from step 604 to step 602 to read out the next existing tree from the memory.
 7 If the decision at step 603 is negative, steps 301, 302 (or 402), 303, 304 and 305
 8 are performed in the same manner as described above on the communication
 9 paths which cannot be accommodated in the read existing tree.

10 Fig. 7 is a block diagram of a further modification of the present
 11 invention in which the optimization reference generation unit 101 of the
 12 previous embodiments is replaced with a realizability decision threshold
 13 generation unit 701 and the tree utilization decision condition generation unit
 14 104 is replaced with an artificial variable embedding unit 704.

15 Fig. 8 is a flowchart for operating the design apparatus of Fig. 7. The
 16 computer initially instructs the tree forming condition generation unit 102 to
 17 perform steps 302 (or 402) of the previous embodiments and then instructs
 18 the optimization reference generation unit 103 to perform step 303 to
 19 produce constraint Equations (2) to (12). At step 801, the artificial variable
 20 embedding unit 704 embeds an artificial variable into each of the constraint
 21 Equations by setting coefficient matrix A, variable vector x, coefficient vector
 22 c. If artificial variable vector is denoted as "y" and the artificial variable of

1 the k-th constraint Equation is denoted as " y_k ", the k-th Equation would be
2 represented as follows:

$$3 \quad a_k x + y_k = c_k \quad (17)$$

4 At step 802, the realizability decision threshold generation unit 701
5 produces an objective function that minimizes the total value of the
6 embedded artificial variables. At step 803, the optimization unit 105 solves
7 the objective function. If the objective function is zero (step 803), the
8 optimization unit proceeds to solve the mathematical programming problem
9 of the constraint Equations to obtain a minimum number of trees (step 804).

10 The previous embodiments of Figs. 5 and 7 can be combined as shown
11 in Fig. 9 such that the existing tree storage and decision unit 501 is associated
12 with the units 701, 102, 103 and 704. The operation of the apparatus of Fig. 9
13 proceeds according to the flowchart of Fig. 10 which combines the flowcharts
14 of Figs. 6 and 8. In Fig. 10, step 803 branches out to step 604 if the objective
15 function is not equal to zero in order to repeat the testing on the next existing
16 tree stored in the memory if all existing trees still have not been tested.

09616672, 071400